



Modeling and imprint fabrication of an infrared wire-grid polarizer with an antireflection grating structure



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HIGHLIGHTS

- We fabricated an infrared wire-grid polarizer with an antireflection grating structure using direct imprint lithography on a chalcogenide glass.
- We formed the Al grating (0.7 fill factor, 100 nm thickness, and 500 nm period) by depositing Al obliquely on the grating.
- The transverse magnetic transmittance of the fabricated polarizer was over 70% in the 8.5–10.5 μm wavelength range.
- The TE transmittance of the fabricated element was around 1% in the 2.5–12 μm wavelength range.

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ABSTRACT

An infrared wire-grid polarizer with an antireflection (AR) grating structure was fabricated using direct imprint lithography on both sides of a low toxicity chalcogenide glass (Sb–Ge–Sn–S system) simultaneously. The AR grating structure was designed using rigorous coupled-wave analysis theory. Silicon carbide with a grating period of 500 nm and glassy carbon with a grating period of 3 μm were employed as molds. After imprinting, a wire-grid polarizer was made by depositing Al obliquely on the grating. The transverse magnetic (TM) transmittance of the fabricated polarizer was over 70% at 8.5–10.5 μm wavelength, although the transmittance of the glass substrate is 62–66%, and the extinction ratio was over 20 dB at 11 μm wavelength. The polarizer has a high TM transmittance and is cheaper and simpler to fabricate as compared with conventional infrared polarizers.

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1. Introduction

Low-cost infrared polarizers have been desired in various applications such as infrared ellipsometry and night vision analysis and others [1–5]. With the significant advance in thermal cameras, demands for infrared devices are increasing. Infrared polarizers are employed to suppress superimposition of reflected images in particular. However, conventional infrared polarizers (wire-grid polarizers) consist of metal wires with hundreds nanometer width that are deposited on an infrared-transmitting material such as Si, Ge, anodic alumina, chalcogenide glass, CaF_2 , and BaF_2 [6–10]. Therefore, microfabrication methods such as expensive lithography

and dry etching entail various problems in their complex process flow, high costs of processing equipment, and low process rates.

To obtain low-cost polarizers for use in thermal imaging, the following conditions must be satisfied: starting materials has to be inexpensive and the fabrication process has to be efficient. To meet these conditions, imprint lithography is attracting interest in the production technology of nanostructured optical devices, since this method has proved to be efficient for duplicating nanostructures with high throughput, good fidelity, and low cost. Some researchers formed nanostructures on resin or oxide glasses by using ultraviolet-imprinting or thermal-imprinting processes [11–16]. However, these materials are not transmissive in the infrared range. Recently, direct thermal-imprinting processing has been conducted on a chalcogenide glass, that are transmissive in the infrared range. However, thermal imprinting is difficult to

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achieve on conventional chalcogenide glasses, since they contain such toxic elements as arsenic (As) and selenium (Se).

Chalcogenide glasses have been studied intensively recently because of their unique optical properties: high transparency in the infrared bands, and markedly low-characteristic temperature, e.g. glass transition temperature $T_g < 300$ °C. However, chalcogenide glasses present inherent disadvantages that limit the feasibility of their use: conventional chalcogenide glasses contain toxic materials such as arsenic (As) and selenium (Se) [17–19]. One type of chalcogenide glass (ILR-SF®1; Isuzu Glass Co. Ltd.) has good transmission at 0.85–11 μm wavelength, a refractive index of 2.7 at 10 μm wavelength, a low glass transition temperature (230 °C), and low toxicity. This glass consists mainly of sulfur (more than 60 mol%) [20,21].

In a previous study, wire-grid polarizers, those consist of the low toxic chalcogenide glass (Sb–Ge–Sn–S system) substrate and Al grating with subwavelength periods, had been fabricated by using the two beam interference exposure and imprint process, which exhibited high extinction ratio in the infrared range [22–24]. However, the reflection loss of this glass was large ($\sim 35\%$), since this glass had a high refractive index [21]. In this study, to enhance the transverse magnetic (TM) transmittance, we designed an antireflection (AR) grating structure in the infrared range, and fabricated a wire-grid polarizer with an AR grating structure by using direct imprinting process on both sides of the glass.

2. Optimization of AR grating structure in the infrared range

The chalcogenide glass exhibits high reflectance (21%) on the surface because of the high refractive index (2.7). The transmittance of the chalcogenide glass substrate is 65% at the 10 μm wavelength. The reflectance on the surface of chalcogenide glass has to be reduced to attain a high transmittance. A subwavelength grating structure is effective to reduce the reflectance [25]. Considering application for infrared cameras, we examined suitable AR structure in the 9–11 μm wavelength range. The transmittance of a chalcogenide glass with the AR grating structure was calculated by using the rigorous coupled-wave analysis theory (RCWA) [26,27]. Consider the model of grating structure on a chalcogenide glass as shown in Fig. 1. We simulated the both of TM (transverse magnetic: electric-field vector perpendicular to the grid) and TE (transverse electric: electric-field vector parallel to the grid) transmittances using the RCWA.

First, we examined the dependence of the grating depth d . Each grating cross section is assumed to be rectangular, and the grating period Λ , the fill factor f , and the refractive index of grating are assumed, respectively, as 3 μm , 0.6, and 2.7 [21]. The fill factor is defined here as the ratio of the single grating width w to the period $[f = w/\Lambda]$. Fig. 2(a) shows transmission spectra as a function of wavelength for the depth of grating from 1 to 2 μm . All of TM spectra were over TE spectra in the 8–12 μm wavelength range, and the peak of TM transmittance was around 79% at 10 μm wavelength. For forming the AR grating structure on one side of this glass substrate, the maximum transmittance of this glass becomes less than 79% due to the index of 2.7, according to the Fresnel reflection theory [28]. As the depth increases, the peak of the transmission

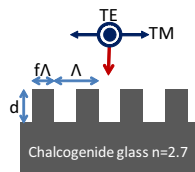


Fig. 1. Model of an AR grating structure of a chalcogenide glass.

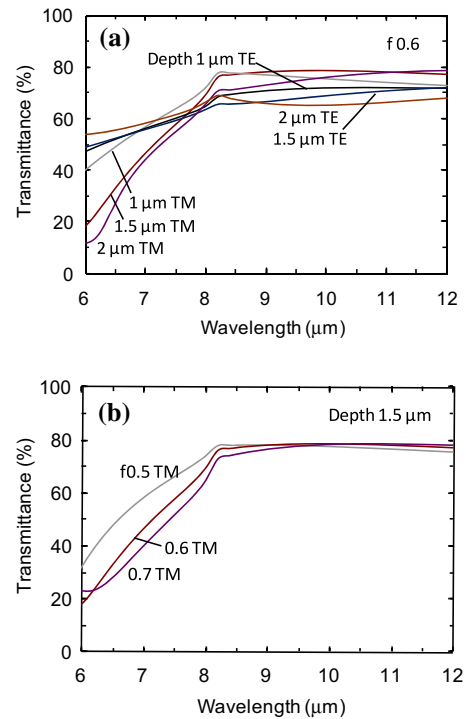


Fig. 2. RCWA simulation results for the TE and TM transmittances of the model shown in Fig. 1 when (a) the grating thickness ($f = 0.6$, $\Lambda = 3$ μm) or (b) the fill factor ($d = 1.5$ μm , $\Lambda = 3$ μm) is changed. The numerals next to the curves denote the polarization, (a) the grating depth, and (b) the fill factor.

spectrum shifted to the long wavelength range. In addition, all of transmission spectra decrease rapidly in short wavelength range. This phenomenon seems to be caused by diffraction, since the condition of $\Lambda \ll \lambda$ does not hold in short wavelength range.

Next, we examined the dependence of the fill factor f . Fig. 2(b) shows the calculated TM transmission spectra as a function of wavelength for the fill factor from 0.5 to 0.7. The depth and the period of grating were assumed, respectively, as 1.5 μm and 3 μm . As the fill factor increases, the peak of TM spectrum slightly shifted to longer wavelength with increasing the fill factor, since the effective index increases.

As a result, we found that the peak of TM spectrum shifted to longer wavelength with increasing the fill factor and the grating depth, and TM transmittances for the grating on a chalcogenide glass substrate exceeded 70% in the 8–12 μm wavelength range in case of $\Lambda = 3$ μm , $f = 0.6$ –0.7, and $d = 1.5$ μm as shown in Fig. 2(b). To achieve higher polarization transmittance in the 9–11 μm wavelength range, our target design requires the fill factor of 0.6–0.7 and the grating depth of around 1.5 μm on the chalcogenide glass surface.

3. Fabrication

Silicon carbide (SiC; Admap Inc.) and glassy carbon (GC; Tokai Carbon Co. Ltd.) plates of 25 $\times$ 25 $\times$ 2 mm with optically flat surfaces were used as molds for the imprinting process because previous reports described that SiC and GC have heat-resistance, high mechanical strength, and micro-workability [15,16,22,23]. A GC mold was used to fabricate the AR grating structure, which requires deep grooves because GC reacts effectively to O_2 gas. Fig. 3 shows fabrication process. A WSi film was deposited on SiC or GC plate by using the sputtering method. A photoresist on the SiC plate was exposed to an interference fringe of He–Cd laser beams (325 nm wavelength) to generate the short-period grating

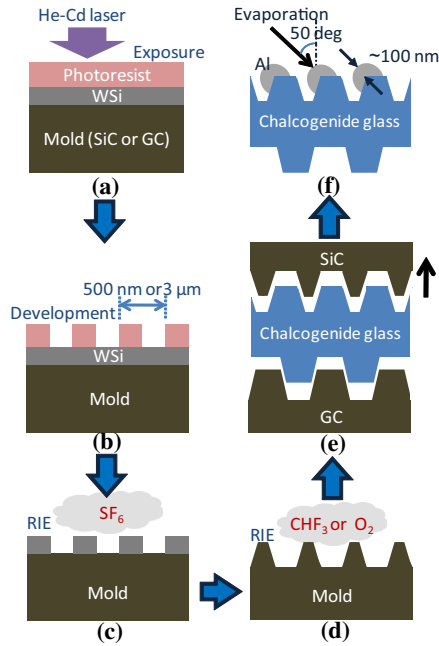


Fig. 3. Fabrication process of the wire-grid polarizer with an AR structure. (a) After a WSi layer is deposited on a SiC substrate by sputtering, a photoresist is coated onto the WSi layer. Then, a He–Cd laser beam is irradiated by the two-beam interference method or the drawing method. (b) The photoresist grating is formed by development. (c), (d) The WSi layer and a SiC or GC plate are etched by using the RIE. (e) The grating structures of SiC and GC molds are imprinted on both sides of a chalcogenide glass. (f) Al was deposited by thermal evaporation on the sidewalls of the grating (500 nm period) from an oblique direction.

structure. The incident angles of the laser beams were around 20° . A photoresist on the GC surface was exposed to the He–Cd laser (442 nm wavelength) with the beam scanned at a speed of 2 mm/s. After rinsing off the exposed resist, the WSi was etched using an inductively coupled plasma reactive ion etching apparatus (RIE, Samco RIE-200iP; Samco Inc.). SF_6 was used as the etching gas of WSi. Finally, the residual photoresist was removed. SiC and GC were etched by using CHF_3 gas and O_2 gas, respectively. Figs. 4 and 5 show scanning electron micrograph (SEM) images of the

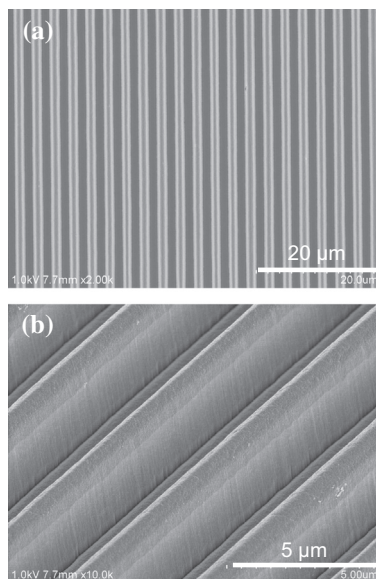


Fig. 4. SEM images of the GC mold.

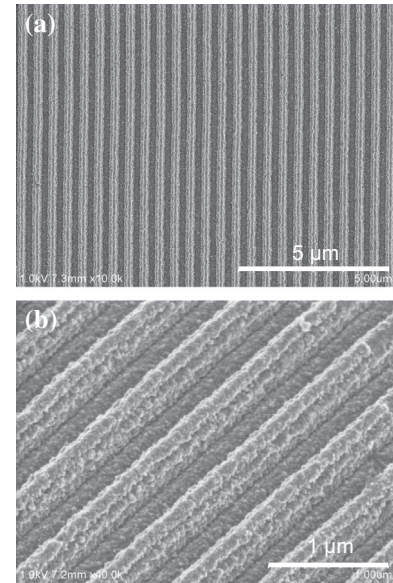


Fig. 5. SEM images of the SiC mold.

fabricated molds. As Figs. 4 and 5 show, grating periods Λ , fill factors f , and depths d of GC and SiC molds were $\Lambda = 3 \mu\text{m}$, $f = 0.4$, $d = 1.94 \mu\text{m}$ (GC mold), and $\Lambda = 500 \text{ nm}$, $f = 0.5$, $d = 230 \text{ nm}$ (SiC mold), respectively. The roughness and the degraded grating shape of SiC mold (Fig. 5) is attributable to the Ar ion etching condition that was used to clean the grating surface before imprinting.

Glass imprinting was carried out using a pressing machine (GMP-415V; Toshiba Machine Co. Ltd.). SiC plate with a grating of a 500 nm period was set as the upper mold, and GC plate with grating of 3 μm period was set as the lower mold in the pressing machine. The grooves of the upper and lower molds were mutually parallel. Glass with 12 mm diameter and 2 mm thickness was set between the molds. For this study, the imprinting temperature, pressure, and time were, respectively, 253°C , 3.8 Pa, and 90 s. Before imprinting, the pressing chamber was filled with N_2 gas to minimize the residual O_2 gas. The upper mold was removed from the

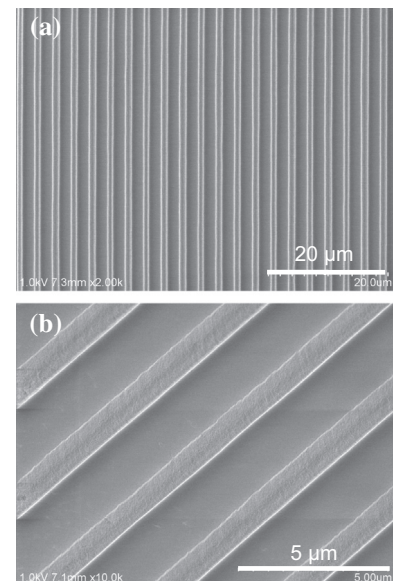


Fig. 6. SEM images of the chalcogenide glass deformed by the imprinting process with the GC mold shown in Fig. 4.

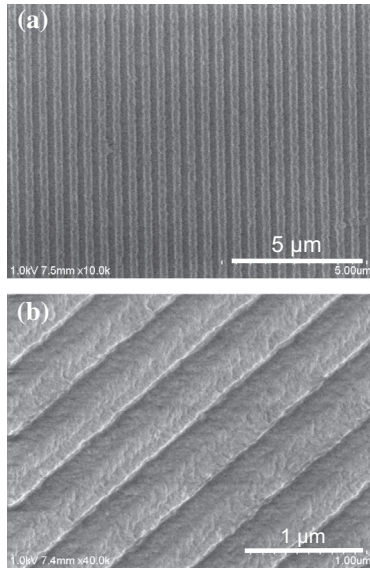


Fig. 7. SEM images of the chalcogenide glass deformed by the imprinting process with the SiC mold shown in Fig. 5.

glass after pressing at an elevated temperature. Then the glass was removed from the lower mold after cooling. The glass surface was observed using SEM. As presented in Figs. 6 and 7, gratings with 3 μm pitch and 500 nm pitch were obtained on both chalcogenide glass surfaces. The depth d and the fill factor f of the grating with 3 μm pitch or 500 nm pitch were, respectively, 1.55 μm and 0.7, and 180 nm and 0.5, the AR grating structure of the calculated value equivalent was obtained. The depth difference between the mold and the imprinted glass result from the thermal shrinkage of the glass. To fabricate an infrared wire-grid polarizer, Al was selected as the wire material because it has a high extinction coefficient. Then Al was deposited on the grating at an oblique angle (between a beam incident on a surface and the line perpendicular to the surface) using thermal evaporation. Fig. 8 presents an SEM micrograph of the element-coated Al film. An Al with around 100 nm thickness was coated onto the grating at 50°. To obtain the high polarization effect and to suppress the reduction of the TM transmittance, metal grating thickness of ~ 100 nm was deposited.

4. Optical characterization and results

Transmittances of the fabricated element were measured using Fourier transform infrared spectroscopy (FTIR IRAffinity-1; Shimadzu Corp.). The probe light was polarized with a stack of two wire-grid polarizers (BaF₂ substrate, IGP227; Specac Ltd.). Fig. 9 shows polarization transmission spectra of the fabricated element. The transmittance for the TM polarization exceeded 70% in the 8.5–10.5 μm wavelength range and the maximum value was 76% (9.5 μm wavelength). This transmittance was higher than that of a chalcogenide glass; e.g., 65% at 9.5 μm wavelength. The TE transmittance of the fabricated element was around 1% in the 2.5–12 μm wavelength range. The extinction ratio of the element was 19 dB at 10 μm wavelength. It was greater than 20 dB at 11 μm wavelength, as shown in Fig. 5(b). Here we defined the extinction ratio as $10 \log(T_{\text{TM}}/T_{\text{TE}})$, in which T_{TM} and T_{TE} denote the transmittances for TM and TE polarized light, respectively.

5. Discussion

As shown in Fig. 9, the TM transmittance at 9.5 μm wavelength was enhanced from 66% to 76%. When the AR grating structure is

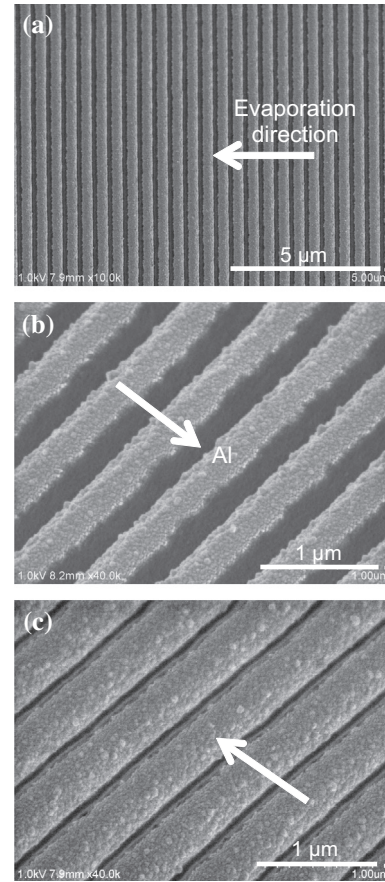


Fig. 8. SEM images of the chalcogenide glass with the deposited Al film (~ 100 nm thickness) by evaporation on the substrate depicted in Fig. 7. The arrow direction shows evaporation direction.

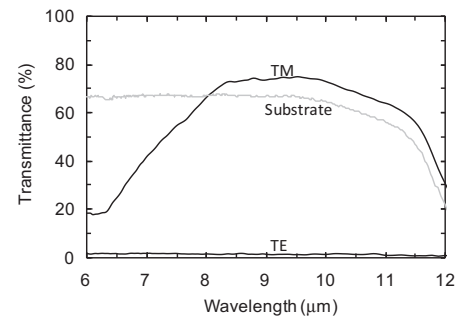


Fig. 9. Transmission spectra of the fabricated element and a chalcogenide glass substrate (2 mm thickness). TE and TM indicate the polarization directions.

formed on one side of this glass substrate, the maximum transmittance of the substrate is assumed to be less than 79% as described above. This means that the grating with 3 μm period functioned as an AR. The calculated value agrees almost well this experimental value as shown in Figs. 2(b) and 9. The reductions of TM transmission spectrum in short wavelength range and over 10 μm wavelength was caused by the effect of diffraction as described above and by the absorption of chalcogenide glass, respectively. Higher transmittance and extinction ratio will be attained in the short wavelength range if the wire-grid period is decreased through improvement of the lithography process. In addition, to enhance the extinction ratio further, increase in the Al grating thickness is effective, since it reduces the TE transmittance [9]. Another reason

for the TE transmission leakage may be the misalignment of the Al grating direction; i.e., the direction of the AR grating was not completely parallel to the wire direction in the current sample. Therefore, we have to consider the effect of the structured birefringence; i.e., as this AR grating acted as a wave plate, TE polarization might have been transmitted slightly. Therefore, pillar structures are preferred to eliminate the structural birefringence [16,29].

6. Conclusion

We designed AR grating structures and succeeded in imprinting simultaneously on both side of the low toxic chalcogenide glass. As a result, we could fabricate an infrared wire-grid polarizer with an AR grating structure. This wire-grid polarizer consists of an Al grating, which has a 500 nm period, a fill factor of 0.7, 100 nm thickness, and an AR grating structure consisting of 3 μm period, fill factor of 0.7, and 1.55 μm depth on the opposite side of wire grids. The imprinting temperature, pressure and time were standardized, respectively, at 253 °C, 3.8 Pa, and 90 s. Although the chalcogenide glass transmittance is 66% at 9.5 μm wavelength, the polarizer TM transmittance was 76% by forming an AR grating structure using the imprinting process on the opposite surface of wire grids at 9.5 μm wavelength. The extinction ratio exceeded 20 dB at 11 μm wavelength. These experiments verified that imprinting on both sides of a chalcogenide glass is extremely useful to fabricate infrared polarizers. This infrared polarizer is cheaper and simpler to fabricate as compared with conventional infrared polarizers.

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